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High Power Laser for Peening of Metals Enabling Production Technology

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Abstract

Laser shot peening, a surface treatment for metals, is known to induce compressive residual stresses of over 0.040 inch depth providing improved component resistance to various forms of failure. Additionally recent information suggests that thermal relaxation of the laser induced stress is significantly less than that experienced by other forms of surface stressing that involve significantly higher levels of cold work. We have developed a unique solid state laser technology employing Nd:glass slabs and phase conjugation that enables this process to move into high throughput production processing.

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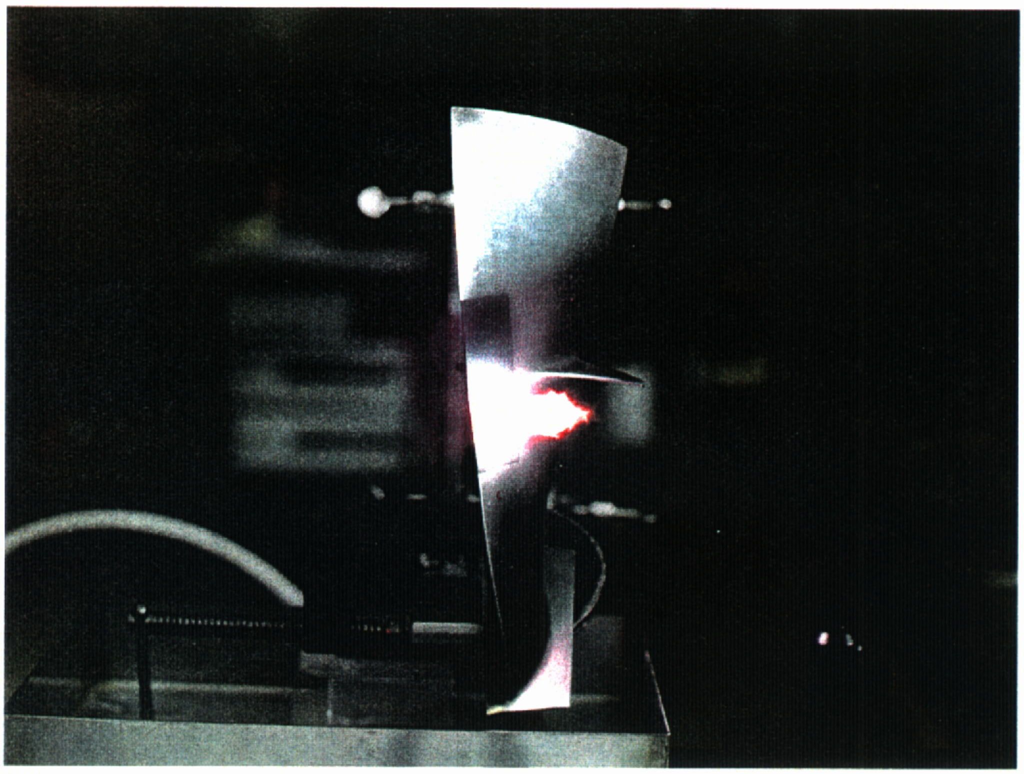


A jet engine fan blade being treated by a Lasershot[sm] Peening System. This system induces deep compressive stress which extends the service lifetime by a factor of three to five times over any conventional treatment. The potential of this process has been known for 20 years but it took a breakthrough development of high energy, high average power laser technology to make the process a commercial reality.

Introduction

Various forms of cold working have been used by industry for many years, to induce beneficial compressive stresses in metals. These include fillet rolling, cold expansion of holes, shot peening and the newest form, laser shot peening. The significant increases in resistance to fatigue, fretting, galling and stress corrosion are well known. Shot peening has been the process most widely used because of its ability to induce these stresses efficiently and inexpensively on parts of complex geometry. The depth of the compressive stress produced by shot peening is limited by the kinetic energy transmitted by the force of the shot and the indention of the surface which can reach 0.030 inch but might leave an undesirable surface finish.

Laser shot peening employs laser induced shocks to create deep compressive residual stress of over 0.040 inch with magnitude comparable to shot peening. Laser shot peening is a more damage tolerant process that has generated sufficiently impressive results that there is keen interest to move it from a laboratory demonstration phase into a significant industrial process. However until now this evolution has been slowed because a laser system meeting the average power requirements for a high throughput process has been lacking.

A laser system appropriate for peening at an industrial level requires an average power in the multi-hundred watt to killowatt range and an energy of around 100 J/pulse and pulse duration of 10s of nanoseconds. Pulsed lasers, with output energies exceeding 10 J, have historically been limited to low repetition rates and consequent low average output power. The large fusion lasers such as Livermore's Nova Laser and the University of Rochester's Omega laser can produce single pulse energies at 1 micron wavelength in the 100 kJ range but are limited to firing about once every two hours for an equivalent average output power of only tens of watts. Commercially available lasers, with outputs of 10 to 100 J, if available

Figure 1. We have developed a unique high energy, high average power laser technology that for the first time enables the commercial introduction of laser peening by providing capability for 10 X increase in throughput over any competing laser system. Pictured above is the Model 100-6 Lasershot^{sm} Peeing system which is the breakthrough technology providing 100 J per pulse output at 10 ns to 1000 ns pulse duration, near diffraction limited beam quality, 6 Hz repetition rate and 600 average power.

at all, are limited to repetition rates around 0.25 Hz, an average power of 25 W. In this paper we report on a highly developed laser technology employing Nd:glass slabs and a master oscillator/power amplifier with wavefront correction called phase conjugation. This technology for the first time pushes the average power output into the 500 W to 1 kW range and meets the requirements for industrial laser peening. Figures 1 and 2 show the 100 J/pulse, 600 W system developed by LLNL and planned for use in the MIC Lasershot^{sm} Peening system.

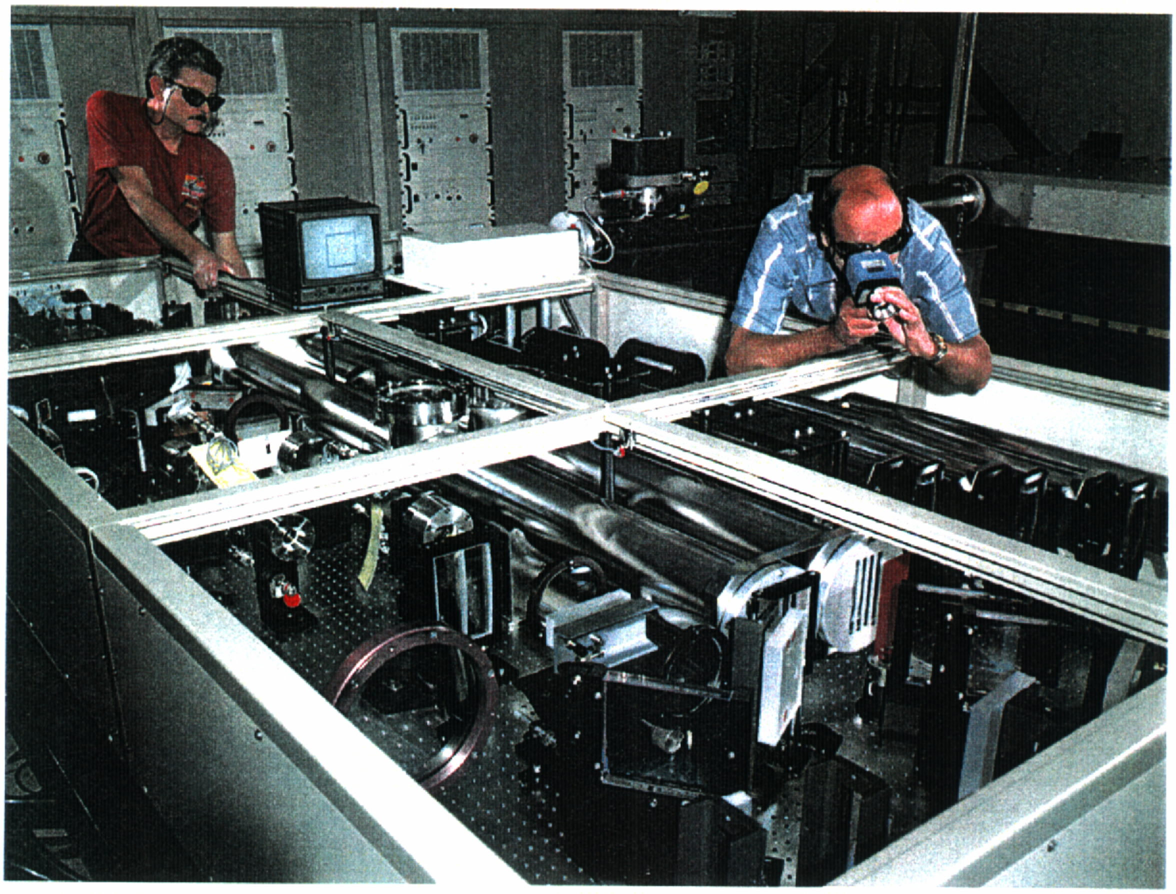


Figure 2. In addition to the high pulse energy, high average power of the Lasershot^{sm} Peening System which is unmatched to within a factor of 10, the laser is a robust, reliable and fully engineered system. Internally, the laser includes advanced technologies such as zig-zag slab amplifiers, passive optical switching with Faraday rotators and stimulated Brillouin scattering phase conjugation. Details of the technology are discussed in the text .

Laser Shock Peening

With the invention of the laser, it was rapidly recognized that the intense shocks required for peening could be achieved by means of tamped plasmas which were generated at metal surfaces by means of high energy density (~200 J/ cm^2) lasers with pulselengths in the tens of nanoseconds range. Initial studies on laser shock processing of materials were done at the Battelle Institute (Columbus, OH) from about 1968 to 1981[1,2]. Excellent recent work has also been reported in France[3]. Figure 3 shows a typical setup for laser peening. Laser intensities of 100 J/cm^2 to 300 J/cm^2 with a pulse duration of about 30 ns can generate shock pressures of 10^4 to 10^5 atmospheres when absorbed on a metal surface (a thin layer of black paint on the surface provides an excellent absorber) and inertially confined with a surface layer (tamp) such as water. These shocks have been shown to impart compressive stresses, deeper than those achievable with standard shot peening. Special techniques for controlling the pulse temporal and spatial shape are used to prevent the high intensity laser from breaking down the water column or generating stimulated processes which reflect the laser energy before reaching the paint surface. With appropriate care given to the setup, impressive results can be achieved from laser peening.

As an example of the laser process, Figure 4 shows the residual stress induced in Inconel by laser peening and contrasts it with typical results achieved by shot peening. Clearly the laser generated shock can be tailored to penetrate deeper into the material and create a significantly greater stress volume. Induced residual stress prevents treated parts from developing cracks due to stress corrosion. Additionally other types of corrosion will require longer periods of time to penetrate the

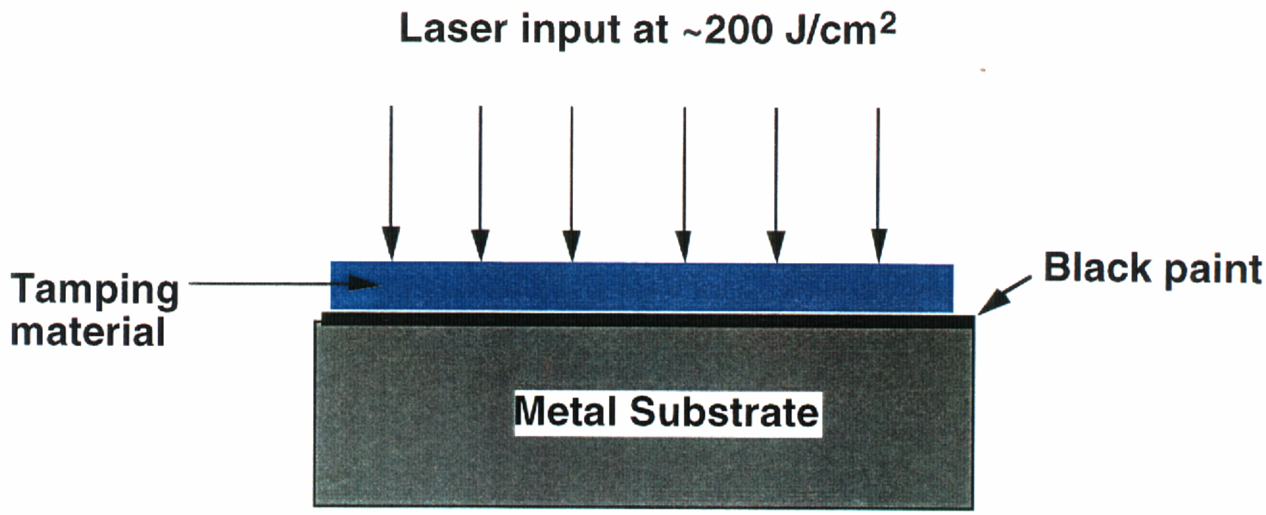


Figure 3. Typical setup for laser peening including a input laser beam of 200 J/cm2 and 30 ns pulselength. The metal layer is covered with a layer of paint to provide light absorption and is covered with a thin water tamping layer to contain the shock.

compression layer induced by Lasershot Peening. Deep residual stress is important for critical areas of components such as turbine blades because it prevents debris damage from penetrating beneath the compressive layer. Foreign object debris (FOD) picked up in operation can often generate damage sites which penetrate a thinner compressive layer and hence become an initiation point for fatigue cracks.

Depth of Residual Stress - Inconel 718

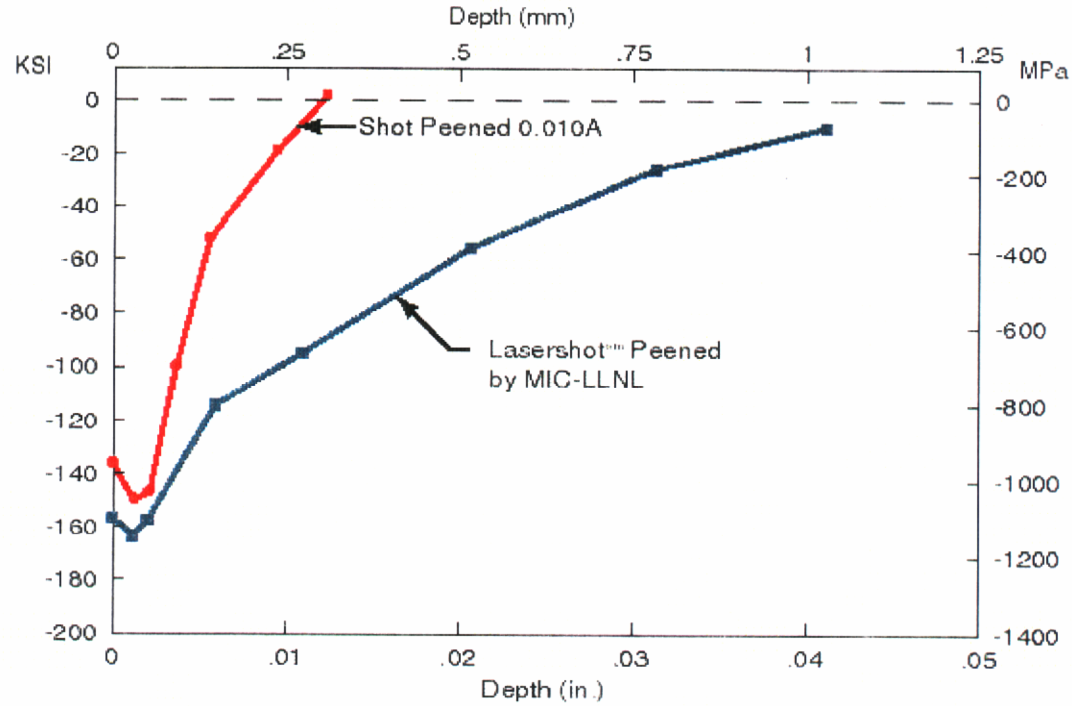


Figure 4. Residual stress induced by laser peening can be made deeper and with significantly greater stressed volume than conventional shot peening.

Another important element in obtaining deep residual stresses is the use of successive shocks to drive the stress deeper and deeper while not exceeding materials limits at the surface. Figure 5 shows results of successive applications to a titanium surface (Ti-6Al-4V) of laser pulses at 200 J/cm^2 and pulse duration of 30 ns. As can be seen, the application of a first and then a second shock successively drives stress deeper and into the material.

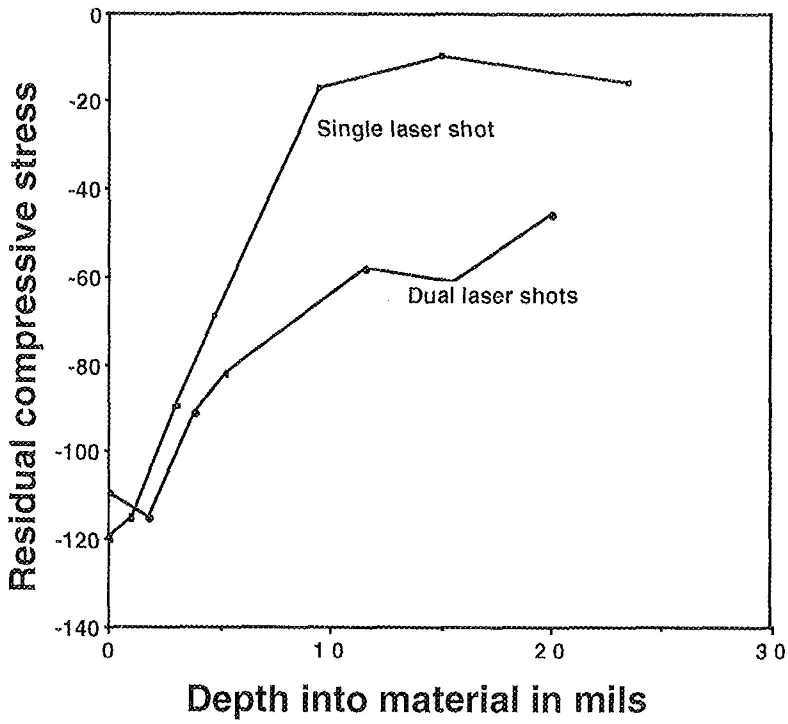


Figure 5. A first and then second lasershot pulse can generate successively deeper residual stress and thus larger stress volume.

Most metals can be successfully lasershot peened. Figure 6 and 7 show other important aerospace materials peened by the laser process. Both show the excellent deep depth of compressive stress.

Depth of Residual Stress - Rene 95

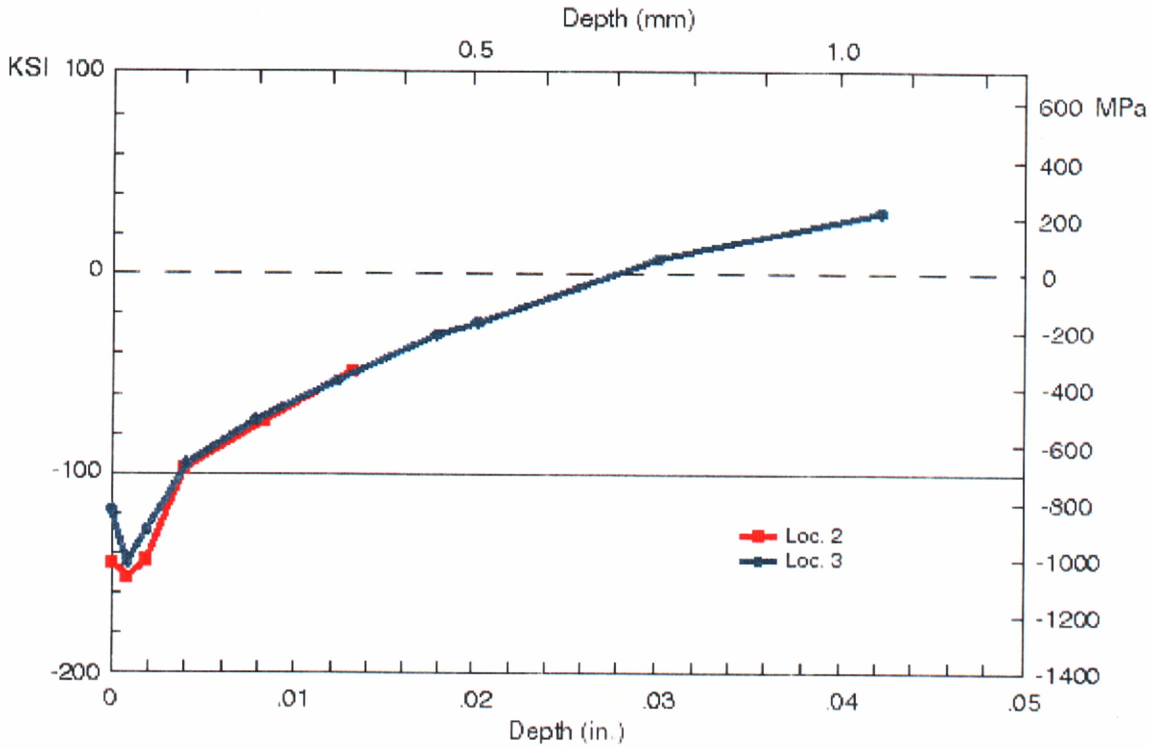


Figure 6. Compressive stress extending to depths of 30 mils is achieved in Rene 95 with single shots of the laser peening system

In recently reported work by P. Prevey, D. Hombach and P. Mason of Lambda Research, a detailed study was done of thermal relaxation of the layer of compression induced by shot peening, gravity peening and laser shocking in Ti-6Al-4V and Inconel 718[4] at temperatures of 230 C to 400 C. For shot and gravity peening the repeated dimpling of the surface results in a highly cold worked layer. Conventional shot peening produces from 10% to 50% cold work. Gravity peening utilizes fewer impacts with larger shot, producing a less cold worked surface layer. The laser process produces remarkably little cold working of the surface (1% to 2%) because only a single or a few deformation cycles are required. The authors find that the initial thermal relaxation of highly clod worked surfaces can be far more rapid than previously realized and can result in 50% loss in 10 minutes. However, the laser process, producing minimal cold working of the surface, has exhibited striking resistance to thermal relaxation. No detectable relaxation was produced in the tests at the lower temperature and at the highest temperature, 425 C, only a small loss occurred near the surface.

Depth of Residual Stress - Waspaloy

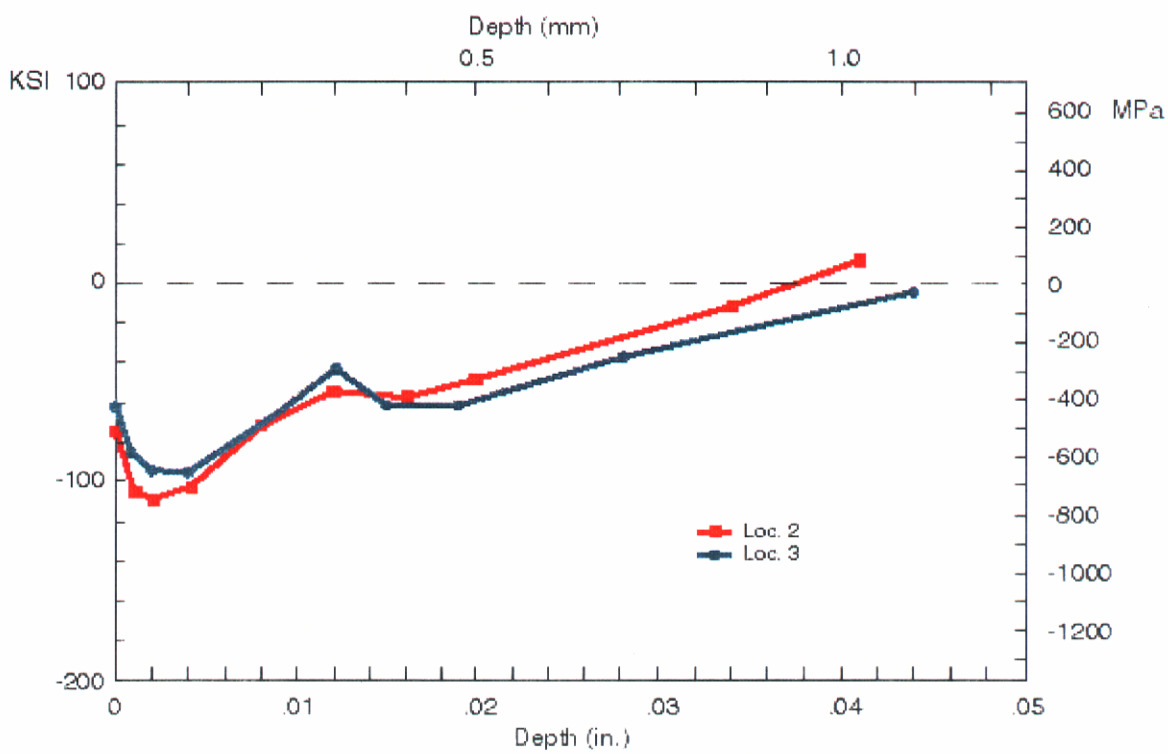


Figure 7. Compressive stress extending to depths of 40 mils is achieved in Waspaloy with the laser peening system

In testing on operational components, such as jet engine fan blades, researchers have shown the laser treatment to be superior for strengthening new and previously damaged fan blades from fatigue and corrosion failure[5]. However the laser technology for doing these types of tests has been limited to producing pulses less than once per second thus peening areas of about 1 square centimeter per second. This rate is acceptable for laboratory demonstrations but clearly not meaningful for cost-effective production. Since the cost of any high energy (100 J) laser is dominated by the hardware required to achieve the single pulse energy, it is imperative to have high repetition rate capability (~10 Hz) in order to keep the production cost per laser shot low.

High power laser technology at LLNL

The Laser Programs Directorate at Lawrence Livermore National Laboratory (LLNL) has been a world leader in developing high energy Nd:glass lasers for fusion applications for the past 25 years. The Nova laser, producing over 120 kJ per pulse, routinely fires 8 to 10 shots per day for dedicated fusion and nuclear effects studies. More recently, the Livermore Laboratory has been directed by the Department of Energy to proceed with building a newer facility, the National Ignition Facility (NIF) which will produce over 2 MJ per pulse of energy in one or several shots per day and is intended to produce more fusion energy release than laser energy input. It is clear that enormous successful investment has been made to develop high energy solid state lasers.

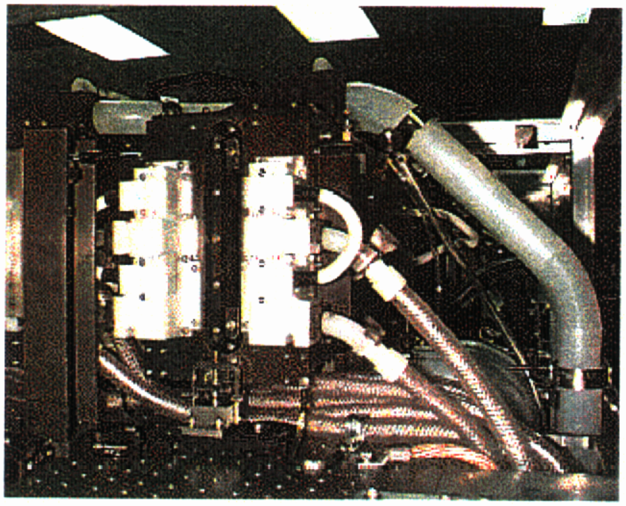
Generating high energy from a solid state glass laser is straightforward. However generating high average power at high energy has been a problem. Over the past decade, LLNL has been developing higher average power systems with energies (depending on the application requirements) of 25 J to 100 J/pulse. This laser technology now demonstrates repetition rates of up to 10 Hz and average powers near 1 kW. The technology development has been supported by the Advanced Research Projects Agency (ARPA) of the Department of Defense and more recently by the US Navy and US Air Force. The ARPA funding was focused on converting the infrared light to high average power x-rays (10 Å). This short wavelength has interest as a light source for proximity printing of advanced generation integrated circuits. The Navy and Air Force funding was directed toward obtaining a light source for long range and highly coherent illumination of missiles and space objects. One of our LLNL lasers is currently in service at a Navy facility at the Kennedy Space Center, Cape Canaveral Florida and a second more power unit is being delivered to the Air Force Phillips Laboratory, Albuquerque New Mexico. This technology has allowed us to develop a glass laser system with energy of 100 J/pulse, adjustable pulse length from 10 ns to 1 μs, near diffraction limited beam quality and average power up to 600 W. This laser technology is ideal for the laser peening application and by a factor of 20 to 50 exceeds the average power achievable by any commercially available laser technology.

The High Average Power Nd:glass Slab Laser System

A system suitable for laser peening must output an energy in the range of 25 J to 100 J per pulse. The throughput of a peening system will then highly depend on the average pulse repetition rate that the laser can achieve. A laser system based on Nd doped glass gain media is the only identified technology that can realistically achieve this type of energy output with acceptable pulselength. Such a system is typically based on an oscillator and one or more rod amplifiers which are optically pumped by flashlamps. As an unavoidable consequence of providing the optical gain, the flashlamps deposit heat into the glass. This heat must be removed at a rate commensurate with the rate of deposition, that is, the pulse rate of the laser. Thus the glass must be cooled, typically by flowing water. As the glass is simultaneously heated and cooled a thermal gradient develops from the center to edge of the glass. This gradient stresses the glass, inducing wavefront deformation and very significantly depolarization of the beam. Thus the thermal loading of the laser gain media is a major limitation to the available average power that can be extracted from the laser. As the repetition rate of the laser is increased, the thermal loading correspondingly increases and degenerates the laser performance often depolarizing and aberrating the laser beam to the point where the laser optics damage. In the limit, the loading will fracture the glass. The LLNL laser design alleviates this thermal problem in three ways; 1) the slab gain medium is pumped in a highly uniform manner minimizing depolarization and distortion, 2) the laser beam is propagated through the slab in a zig-zag manner to average out much of the wavefront distortion and 3) SBS phase conjugation highly corrects residual wavefront distortions.

The LLNL high average power Nd:glass laser technology is comprised of a single master oscillator and one or more power amplifiers. The amplifier gain medium is neodymium (Nd) doped phosphate glass APG1 supplied by Schott Glass Technologies Inc. or HAP4 supplied by Hoya Corporation. The glass is configured in a slab shape to allow one thin dimension for rapid heat removal. Typical slab dimensions are 1 cm x 14 cm by 40 cm. Typical Nd doping level is 3×10^{20} cm^{-3} or 2.7% by weight.. Figure 8 shows a cross-sectional view of an amplifier.

Slab amplifier operating in the AIT laser system



Schematic of the amplifier design

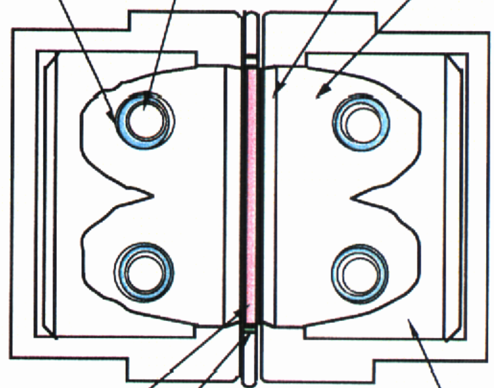


Figure 8. Photograph and cross-sectional view of the Nd:glass laser amplifier. Flashlamp light, tailored for highly uniform illumination by the diffuse reflectors, provides the excitation to the slab. The thin dimension of the slab allows for efficient heat extraction into the water flow. The laser light zig-zags through the slab averaging wavefront distortions.

Unlike a more traditional amplifier where the beam is propagated through the gain medium in a straight line, our design employs a zig-zag path, reflecting the beam internally off the slab faces. As shown in the figure, the slab is positioned in the center of the assembly and has a water cooling channel along both sides formed by the slab face and a reflector window. Two flashlamps on each side pump the slab through the cooling channels. A diffuse reflector surrounds the flashlamps and by appropriate shaping provides uniform optical pumping. The reflector material is made of a Teflon-like substance called Spectralon machined to a specific shape to tailor the pumping irradiance on the slab surfaces. Designing a thin dimension for the gain medium creates one short path for high heat conduction from the slab center to the cooling water. The resulting high heat transfer efficiently removes the heat buildup and directly increases the repetition rate capability of the laser. Very uniform optical pumping from the reflector assembly results in uniform energy distribution from top to bottom in the slab. At high repetition rates a large thermal gradient develops in the slab from center to edge. However, the laser light is directed through the slab so that the beam propagates in a side-to-side zig-zag manner. This zig-zaging averages the side-to-side thermally induced pathlength differences providing a high quality horizontal wavefront even though there is a significant gradient in this direction.

A representative optical layout for the laser system is shown in figure 9. The output of the oscillator transmits through a Faraday isolator and then in P

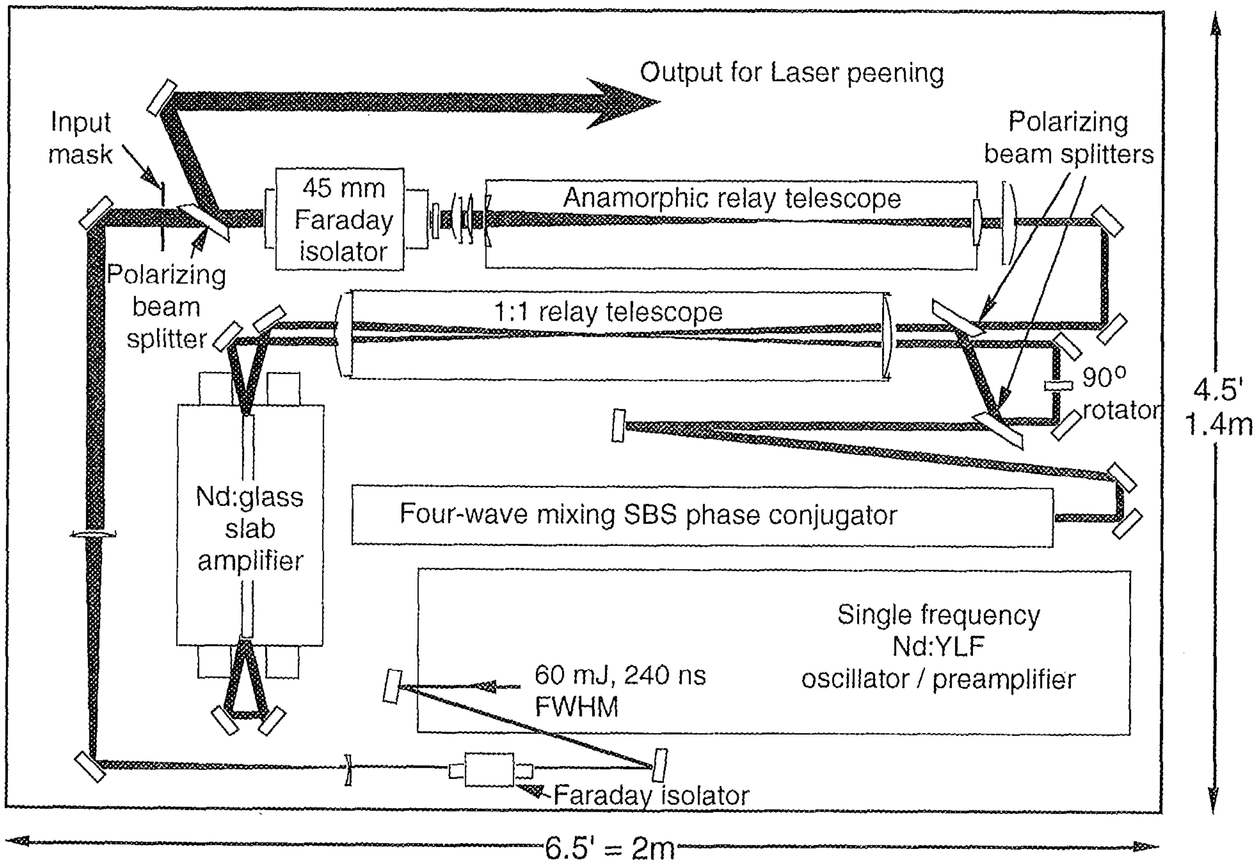


Figure 9. Typical layout of the high energy Nd:glass laser system with repetition rate of 6 to 12 Hz. The high quality master oscillator output is amplifier by means of 8 passes through the slab amplifier. The SBS phase conjugator provides necessary wavefront correction so that the output is near diffraction limited beam quality.

polarization transmits through a polarizing beam splitter. The beam next passes through an input/output Faraday rotator which acts as a passive cavity switch and then still in P polarization transits through the first polarizer within the amplifier cavity. It next transits a relay telescope, double passes the amplifier and then propagates back through the telescope and through a 90 degree rotator. The now S polarized beam reflects off the polarizing beam splitters, transits through the relay telescope and for a second time double passes the amplifier. Passing again through the 90 degree rotator and converting back to P polarization, the beam nowpropagates to the SBS phase conjugator. Within the phase conjugator the beam generates an index grating by means of stimulated Brillouin scattering. This index grating acts as a special kind of mirror, reflecting the beam back but with the phase of the wavefront reversed. The beam retraces it path through the amplifier ring and back to the input/output Faraday rotator. In the output direction the rotator flips the beam to S polarization, allowing it to exit the laser. In these final four passes, the beam amplifies to the desired output energy and very importantly, all phase errors accumulated in the first four amplifier passes are negated in the final four amplifier passes (by summation of phases which are basically identical but reversed in sign) to generate a high power beam with nearly diffraction limited beam quality. By correcting for thermal aberrations our design allows us to extract average powers up to the mechanical limit of the gain medium. Without the phase conjugator the beam quality rapidly degrades as the laser average output power is increased. This degraded beam quality results in reduced focus control of the beam and less power on target. Even more important, the reduced beam quality can lead to intensity "hot spots" within the laser and consequently to self damage of the laser. The SBS phase conjugator, simply and reliably eliminates this problem. Figure 10 illustrates the beam quality of the laser with and without the use of a phase conjugator.

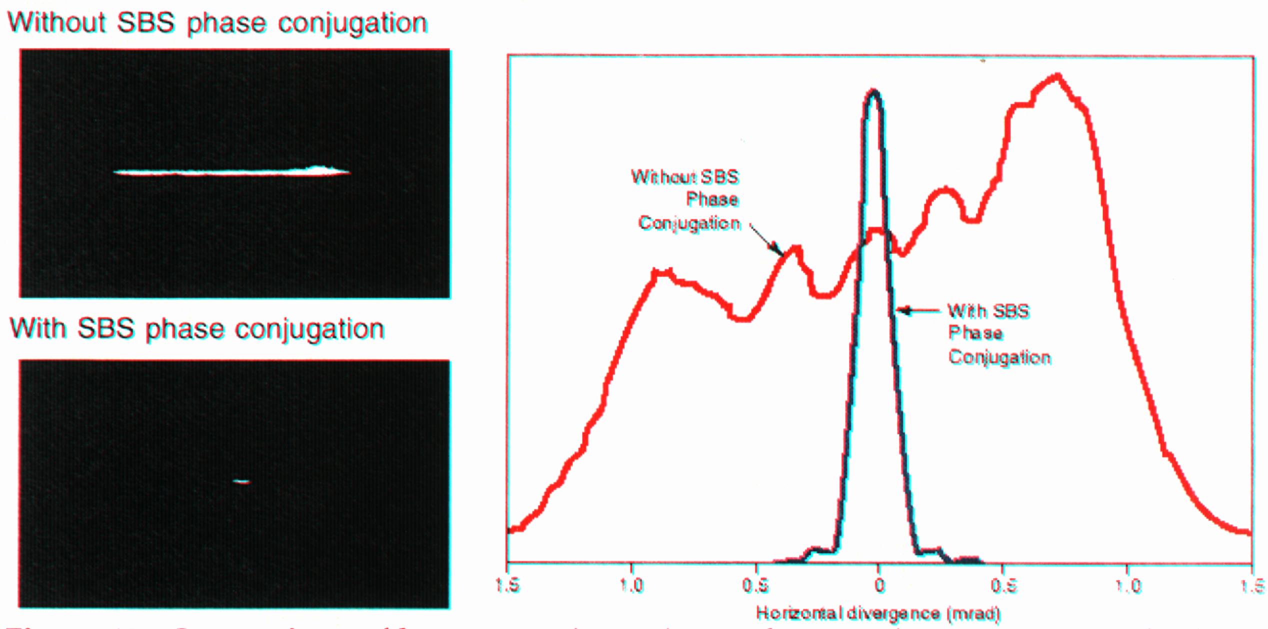


Figure 10. Comparison of laser operation using a phase conjugator or a standard mirror clearly shows the enormous improvement in beam quality in the far field with the conjugator. The rectangular shaped far field profile results from the rectangular near field profile of the glass slab. This data was taken at only 3 Hz operation, half of full laser capability and already shows the dramatic difference .

There are additional significant advantages to the operation of the amplifier system with the SBS phase conjugator. Eight gain passes through the zig-zag slab amplifier can be achieved using passive polarization switching in the regenerative amplifier ring. The fact that the SBS cell provides interstage gain isolation makes this possible since, if it were replaced with a mirror, the small signal gain through eight consecutive gain passes would lead to parasitic oscillation from the small reflective losses of AR coated optical surfaces in the ring or in the output beam.

The SBS phase conjugator also very effectively conjugates the first order aberration of tilt. This greatly reduces the sensitivity of the system performance to small changes of optical alignment in the ring. No change in output power or pointing direction during operation are observed for large mirror misalignments in the ring. Loss in performance is limited to only to those angular excursions that result in vignetting of the beams at the edges of the amplifier slab.

Finally and specifically for the laser shock peening application, the SBS phase conjugation naturally produces a fast rising edge laser pulse. Because the SBS is a non-linear process with a definite threshold, the phase conjugator does not respond to the initial low intensity buildup typically associated with a laser pulse. The beam returned by the conjugator has its leading edge "clipped" and thus the returned pulseshape has a sharp, sub-nanosecond rising edge. The fast rising pulse is critically important for laser peening because it reduces the possibility of breakdown or other non-linear processing occurring in the tamping material and allows the full pulse energy to reach the paint area on the metal and thus contribute to building the high intensity shock.

Although not needed for shock peening, the laser's high output beam quality enables efficient conversion of the infrared output light into green light. Conversion efficiencies for this laser technology range from 65% at 1 μs duration pulses to over 80% for 10 ns pulses.

Achieving high output energy from a solid state laser is limited by the physical size of the gain medium, the saturation fluence of the material and the damage fluence that can be accommodated. Increasing the height of the slab becomes impractical due to the cost of large optics. Increasing the length effects the gain and amplified spontaneous emission limits. Increasing the thickness directly decreases the average power capability. However using our newly demonstrated technique of phase locking multiple apertures we can scale the laser output into exciting new levels of energy and average power[6]. In this technique a single laser oscillator feeds multiple laser amplifiers and the beams are recombined into a single phase conjugator which effectively locks the separate channels into a single coherent laser beam. The far field beam quality is near the physical diffraction limit, the laser energy is that of the combined multiple apertures and the repetition rate is the higher one associated with a single laser slab. Figure 1 shows the highly engineered 100 J/pulse glass slab laser system packaged and ready for deliver to the US Air Force Phillips Laboratory. This laser will be used in a long (600 ns) pulse mode for space object imaging. Its output energy of 100 J/pulse and its short average power capability of 600 W offers an ideas source for lasershot peening.

A performance table.

Manufacturer Model	MIC/LLNL Lasershot 100-6	Advantage of Lasershot 100-6
Pulse Energy	100 J	Required
Repetition rate	6 Hz	> 10 X throughput advantage
Average power	600 W	> 10 X throughput advantage
Spatial shape	Rectangular	Improves coverage efficiency by >25%
Throughput rate capability	11,000 cm^2 / hr	Reduces cost per part treated
Pulse sharpening hardware required	NONE - Automatically provided by SBS	Reduces system capital cost by $50,000 and greatly improves reliability
High quality beam smoothness	Automatically near perfect at all powers	Eliminates pitting and spalling and consequent damage and rejection of expensive parts

There is no commercially available laser peening system that can compare with the throughput capability, rectangular spatial profile and spatial beam control of the Lasershot^{sm} Peening System. The high pulse repetition rate enables 10X greater system throughput and the rectangular beam profile enables more efficient coverage.

Our product improves upon competitive products

The most significant feature of our laser peening system is the high repetition rate afforded by the laser. The lack of meaningful laser repetition rate has held back the laser peening technology from meaningful industrial introduction for many years. Now, the breakthrough laser technology offered in our product for the first time enables acceptably high treatment area rates to generate the high throughputs required for industrial treatment of components such as jet engine fan blades and rotors. Since the cost of a laser peening system is fundamentally driven by the hardware required to produce the output energy, typically 100 J, the 10X advantage of our product's repetition rate will be translated to comparable increases in throughput per hour. With a nominally similar cost in capital investment, the higher repetition rate means a reduction in cost per part treated.

Competitive products do not control the wavefront in an active manner as done in our system by the SBS phase conjugator technology. Consequently, the competing systems are potentially close to optical damage limits as off-normal operation leads to increased thermal loading and consequent wavefront distortion. Wavefront distortion can directly lead to self-focusing which catastrophically destroys laser rods and high value optics. The SBS phase conjugator employs a passive, inexpensive cell of liquid material which automatically maintains wavefront near the physically allowable perfect limit. The conjugator allows our system to run at 10X higher average power and throughput where other systems are limited by optical damage.

Competitive products employing cylindrical rod designs naturally produce a round output beam spatial profile. Treatment of extended areas then requires overlapping spots in an inefficient manner. The naturally rectangular profile of the slab laser technology allows full area coverage with each spot placed directly adjacent to the next.

Competitive products require rather elaborate hardware and techniques to achieve the sharp pulse risetimes necessary for efficient shock production. These techniques involve exploding foils and/or fast switching, accurately timed Pockels cells that use high voltage pulsed supplies. The SBS wavefront correction naturally produces a sharp rising pulse without additional hardware.

The high average power available from the Nd:glass slab laser system enables for the first time a high throughput laser peening system. Assuming that 200 J/cm^2 is required to generate an effective 10 kBar shock, the LLNL laser system, operating at 100 J per pulse and 6 Hz repetition rate, will have a throughput capability in excess of 10,000 cm^2 per hour for single pulse applications and 5,000 cm^2 for dual pulse applications. Upgrading the laser with the newly developed APG-2 laser glass and thus doubling its average power output, the throughputs can be increased to 20,000 cm^2 per hour and 10,000 cm^2 per hour, respectively.

Summary

We have developed a class of laser system at the 100 J level with average power capability pushing toward 1kW. Its new technology includes uniformly pumped zig-zag slab gain media, master oscillator/power amplifier (MOPA) architectures and phase conjugation, to minimize the effects of thermal loading and correct the problems generated by it. This technology enables for the first time industrial application of a high throughput laser peening process.

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